

conditions with ~7 mbar in the atmosphere, <300 mbar in the regolith, and <5 mbar in the caps.

Such scenarios only exist if the early Sun was brighter than standard solar models suggest, if greenhouse gases other than CO₂ were present in the early atmosphere, or if the polar albedo is significantly lower than 0.75. However, these scenarios generally require the storage of large amounts of CO₂ (>1 bar) in the carbonate reservoir. If the warm and wet early Mars constraint is relaxed, then we find best overall agreement with present-day reservoirs for initial CO₂ inventories of 0.5–1.0 bar. We also find that the polar caps can have a profound effect on how the system evolves. If the initial amount of CO₂ is less than some critical value, then there is not enough heating of the poles to prevent permanent caps from forming.

Once formed, these caps control how the system evolves because they set the surface pressure and hence the thermal environment. If the initial amount of CO₂ is greater than this critical value, then caps do not form initially, but can form later on when weathering and escape lower the surface pressure to a point where polar heating is no longer sufficient to prevent cap formation and the collapse of the climate system. Our modeling suggests this critical initial amount of CO₂ is between 1 and 2 bar, but its true value will depend on all factors affecting the polar heat budget.

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POSSIBLE TEST OF ANCIENT DENSE MARTIAN ATMOSPHERE. W. K. Hartmann¹ and S. Engel², ¹Planetary Science Institute, Tucson AZ 85705, USA, ²Lunar and Planetary Lab, University of Arizona, Tucson AZ 85721, USA.

We have completed preliminary calculations of the minimum sizes of bolides that would penetrate various hypothetical martian atmospheres with surface pressures ranging from 6 to 1000 mbar for projectiles of various strengths (weak icy comet, carbonaceous bodies, coherent chondrite, iron). The calculations are based on a program kindly provided by C. Chyba [1]. These numbers are used to estimate the diameter corresponding to the turndown in the crater diameter distribution due to the loss of these bodies, analogous to the dramatic turndown at larger size already discovered on Venus due to this effect.

We conclude that for an atmosphere greater than a few hundred millibars, a unique downward displacement in the diameter distribution would develop in the crater diameter distribution at $D \sim 0.5$ –4 km, due to loss of all but Fe bolides.

Careful search for this displacement globally, as outlined here, would allow us to place upper limits on the pressure of the atmosphere contemporaneous with the oldest surfaces, and possibly to get direct confirmation of dense ancient atmospheres.

We are currently searching for support to refine the calculations and conduct the necessary careful search in the cratering records.

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GROUND BASED MONITORING OF MARTIAN ATMOSPHERIC OPACITY. K. E. Herkenhoff¹ and L. J. Martin², ¹Mail Stop 183-501, Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA, ²Lowell Observatory, Flagstaff AZ 86001, USA.

The amount of dust in the martian atmosphere is variable in both space and time [1,2]. The presence of aerosols in Mars' atmosphere complicates quantitative analysis of martian surface properties [3–7]. Dust storms have been observed telescopically for almost 200 yr and are known to have major effects upon the structure and circulation of the martian atmosphere [8,9]. Great dust storms tend to occur during the southern spring and summer [2] and may be an important mechanism by which dust is transported into the polar regions [10]. It is widely believed that the martian polar layered deposits record climate variations over at least the last 10–100 m.y. [11–18], but the details of the processes involved and their relative roles in layer formation and evolution remain obscure [19]. The layered deposits are widely believed to be the result of variations in the proportions of dust and water ice deposited over many climate cycles [13–15]. However, the amount of dust currently transported into the polar regions is unknown, as are the effects of global climate changes on dust transport. In order to infer the climate history of Mars from geologic evidence including the polar layered deposits, the current cycling of dust through the martian atmosphere must be understood. In addition, future missions to Mars (including possible human exploration) will require better knowledge of the likelihood and severity of martian dust storms.

Zurek and Martin [2] found that "planet-encircling dust storms do not occur every Mars year, and . . . that there may have been periods of several successive years without such storms." The clarity of Mars images taken during recent oppositions suggests that the martian atmosphere has been less dusty recently than in previous years [20]. Hubble Space Telescope images of Mars show that the dust opacity was less than 0.06 in December 1990 [21]. Ingersoll and Lyons [22] proposed that martian great dust storms are chaotic phenomena, influenced by the amount of "background" dust in the atmosphere. However, their analysis was hindered by gaps in the historical record of martian dust opacity. Martian dust storms can be detected only when Mars is relatively close to Earth, so a complete seasonal or interannual history of dust storms is impossible to obtain from groundbased data alone. The optical depth of aerosols in the martian atmosphere between dust storms has been determined primarily from spacecraft data [23,24], but can also be inferred from groundbased observations [5]. Groundbased images of Mars show that atmospheric dust opacity significantly affects the photometric behavior of the planet. Lumme [5] modeled martian limb brightening using high-quality visible-light photographs taken on September 3, 1973. The optical thickness (0.16) and single-scattering albedo (0.55) at 435 nm that he derived are consistent with more recent results using Viking Orbiter violet-filter television data [4,6,25,26], indicating that groundbased data may be used to determine the scattering properties of the martian atmosphere. As shown below, Mars limb brightening data can be used to determine the opacity of aerosols in the martian atmosphere between dust storms.

We have developed a model for Mars surface and atmospheric scattering based on equations (1)–(6) in Hillier et al. [27]. This formulation was chosen for its speed of computation and because it accounts for the spherical geometry of atmospheric scattering at

high emission angles, i.e., near the planetary limb. The atmosphere is assumed to be optically thin in this model, so optical depths greater than 0.2 are not modeled using this formulation. Hapke's bidirectional reflectance function is used to model the surface scattering, assuming a phase function of the form $P(a) = 1 + b \cos(a)$, where a is the phase angle. Dust was assumed to be responsible for all the atmospheric scattering in this model (Rayleigh scattering in the martian atmosphere is insignificant in visible light).

The effects of turbulence in the terrestrial atmosphere ("seeing") upon groundbased Mars images were simulated by convolving a smearing function similar to that used by Lumme [5] with theoretical profiles. The results of this convolution indicate that changes in optical depth of 0.1 can be observed from Earth even with 2 arcsec seeing if the atmosphere is optically thin (small changes in opacity cannot be distinguished in the optically thick case). The shape of the photometric profile is not diagnostic of scattering in all cases, but the absolute reflectance can be used to infer the optical depth of dust in the atmosphere. Therefore, it should be possible to determine the optical depth of aerosols in an optically thin martian atmosphere using well-calibrated groundbased images of Mars. To test the viability of this method, we are comparing Viking data with nearly simultaneous groundbased photographs of Mars taken during the 1977-1978 apparition. The results of this comparison will be reported at the workshop.

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MARS ATMOSPHERIC LOSS AND ISOTOPIC FRACTIONATION BY SOLAR-WIND-INDUCED SPUTTERING AND PHOTOCHEMICAL ESCAPE. B. M. Jakosky¹, R. O. Pepin², R. E. Johnson³, and J. L. Fox⁴, ¹Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder CO 80309, USA, ²School of Physics and Astronomy, University of Minnesota, Minneapolis MN 55455, USA, ³University of Virginia, Charlottesville VA 22908, USA, ⁴State University of New York, Stony Brook NY 11794, USA.

We examine the effects of loss of Mars atmospheric constituents by solar-wind-induced sputtering and by photochemical escape

during the last 3.8 b.y. Sputtering is capable of efficiently removing all species from the upper atmosphere including the light noble gases; N is removed by photochemical processes as well. Due to diffusive separation (by mass) above the homopause, removal from the top of the atmosphere will fractionate the isotopes of each species with the lighter mass being preferentially lost. For C and O, this allows us to determine the size of nonatmospheric reservoirs that mix with the atmosphere; these reservoirs can be CO₂ adsorbed in the regolith or H₂O in the polar ice caps. We have constructed both simple analytical models and time-dependent models of the loss from and supply of volatiles to the martian atmosphere.

Both Ar and Ne require continued replenishment from outgassing over geologic time. For Ar, sputtering loss explains the fractionation of ³⁶Ar/³⁸Ar without requiring a distinct epoch of hydrodynamic escape (although fractionation of Xe isotopes still requires very early hydrodynamic escape). For Ne, the current ratio of ²²Ne/²⁰Ne represents a balance between loss to space and continued resupply from the interior; the similarity of the ratio to the terrestrial value is coincidental. For Ni, the loss by both sputtering and photochemical escape would produce a fractionation of ¹⁵N/¹⁴N larger than observed; an early, thicker CO₂ atmosphere could mitigate the N loss and produce the observed fractionation as could continued outgassing of juvenile N. Based on the isotopic constraints, the total amount of CO₂ lost over geologic time is probably of order tens of millibars rather than a substantial fraction of a bar. The total loss from solar-wind-induced sputtering and photochemical escape, therefore, does not seem able to explain the loss of a putative thick, early atmosphere without requiring formation of extensive surface carbonate deposits.

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SNC METEORITES AND THEIR IMPLICATIONS FOR RESERVOIRS OF MARTIAN VOLATILES. J. H. Jones, Mail Code SN4, NASA Johnson Space Center, Houston TX 77058, USA.

The SNC meteorites and the measurements of the Viking landers provide our only direct information about the abundance and isotopic composition of martian volatiles [1,2]. Indirect measurements include spectroscopic determinations of the D/H ratio of the martian atmosphere [3]. Here I present a personal view of volatile element reservoirs on Mars, largely as inferred from the meteoritic evidence. This view is that the martian mantle has had several opportunities for dehydration and is most likely dry, although not completely degassed. Consequently, the water contained in SNC meteorites was most likely incorporated during ascent through the crust. Thus, it is possible that water can be decoupled from other volatile/incompatible elements, making the SNC meteorites suspect as indicators of water inventories on Mars.

Multiple Reservoirs of Volatiles on Mars: The covariation of ¹²⁹Xe/¹³²Xe with ⁸⁴Kr/¹³²Xe among the members of the SNC suite strongly implies that there are at least two volatile element reservoirs on Mars [4]. The first, best associated with the Chassigny meteorite, has a solar ¹²⁹Xe/¹³²Xe ratio of ~1 [4]. The second, best associated with shock glasses from the EETA 79001 shergottite, has ¹²⁹Xe/¹³²Xe ~2 [4] and is within error of the Viking measurement of martian air [1]. Because Chassigny is a cumulate igneous rock that appears to have experienced minimal weathering [5,6] and interaction with crustal materials [7] (but see below!), it is assumed here that Chassigny's anhydrous, volatile-element component is derived